EUV IRRADIANCE VARIATIONS MEASURED WITH THE SOHO CORONAL DIAGNOSTIC SPECTROMETER OVER 4 YEARS OF SOLAR CYCLE 23

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ABSTRACT

The Coronal Diagnostic Spectrometer aboard the Solar and Heliospheric Observatory observes the solar EUV spectrum in two bands between 308–379 Å and 513–633 Å, spanning the temperature range from 3×10^4 K to 2.7×10^6 K. The full Sun irradiance can be measured by rastering the instrument over the solar disk. Measurements of the solar irradiance have been made starting 25 March 1997 and continue to the present, ranging from near solar minimum to solar maximum. This presentation extends earlier work by combining data from both before and after SOHO's accident in 1998. Comparisons are made between the CDS measurements, and predictions from the Hinteregger, EUVAC, EUV97, and SOLAR2000 models. Until the recent launch of the TIMED satellite, these measurements were the only current EUV spectral irradiance measurements taken on a regular basis. The high spectral resolution of these measurements, combined with the coverage of a significant proportion of the solar cycle, provide a unique dataset for understanding solar variability in the EUV.

Key words: EUV; Irradiance; SOHO; CDS.

1. THE OBSERVATIONS

The Normal Incidence Spectrometer (NIS) of the SOHO Coronal Diagnostic Spectrometer (CDS) observes spatially resolved spectra in two bands, NIS-1: 308–379 Å, and NIS-2: 513–633 Å. A special observing program allows the full-Sun irradiance to be measured by rastering over the entire Sun. A full scan takes approximately 13 hours, and is performed on a roughly monthly basis. Most recently, this rate has been increased to approximately semi-monthly. Figure 1 shows representative full-Sun NIS spectra. The spectral resolution varies from 0.3 to 0.6 Å, allowing the separation of closely spaced lines. For example, the Si XI line at 303.3 Å can be clearly separated from the He II line at 303.7 Å (both seen in second order).

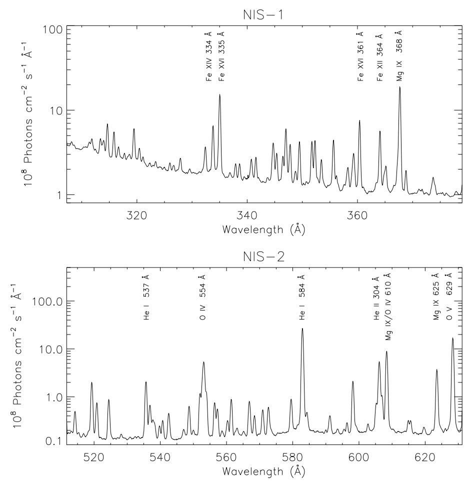

Figure 1. Representative CDS full-Sun irradiance spectra in the two wavelength bands. A selection of prominent lines are identified. Irradiances from 154 separate spectral lines have been extracted. The apparent continuum component is actually due to off-band scattering in the spectrometer.

Data from prior to SOHO's accident in the summer of 1998 was presented in a previous report (Thompson & Brekke 2000). The present work extends that analysis by including data from after SOHO's recovery. A significant fraction of the solar cycle is covered by these measurements, ranging from close to solar minimum to solar maximum.

Comparison of the CDS irradiances to the Solar EUV Monitor (SEM) aboard SOHO, shows that the CDS values are stable to at least the 20% level. This is demonstrated in Figure 2, which is taken from Thompson et al. (2001). A significant part of the difference between CDS and SEM is caused by an underestimation of the Fe XV 284 Å line, unobserved by CDS, which has to be modeled to compare against SEM. The DEM model used did not have sufficient resolution to adequately predict the Fe XV line. It is also probable that the apparent slow slopes in the CDS/SEM ratio are at least partly due to the 284 Å component. Monitoring of the brightnesses of quiet Sun network cell interiors suggest that the CDS sta-

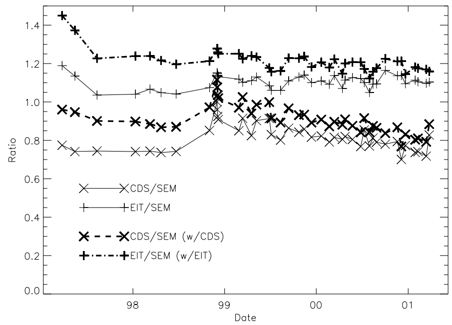

Figure 2. The ratio of the CDS (×) and EIT (+) irradiance measurements to the SEM irradiance. The solid and broken lines represent different ways of analyzing the SEM data, using either the SOLERS22 spectrum (solid) or the CDS or EIT spectrum respectively (broken). The latter are drawn bold, to emphasize that they are the more relevant comparisons.

bility is closer to 10%. Since the solar variability over the solar cycle ranges from ∼40% for transition region lines, to factors of 2 or more for coronal lines, the CDS measurements are of sufficient quality to meaningfully explore the solar cycle variation in the EUV.

Monitoring of synoptic quiet Sun radiances shows that the NIS-2 calibration is the same both before and after SOHO's accident in 1998. However, the post-recovery NIS-1 data must be boosted by a factor of 1.447 to maintain the calibration, while second-order 304 Å in the NIS-2 bandpass must be boosted by 1.167 (Thompson et al. 2001). These correction factors were used in the comparison shown in Figure 2, and have also been applied in the analysis presented here.

2. COMPARISON WITH EUV MODELS

As in Thompson & Brekke (2000), we compared our results against four standard models for the EUV irradiance: Hinteregger (Hinteregger et al. 1981), EUVAC (Richards et al. 1994), EUV97 (Tobiska & Eparvier 1998), and SOLAR2000/v1.20 (Tobiska et al. 2000). The primary purpose of these models is to assist in modeling the interaction of the ionizing radiation from the Sun with planetary atmospheres. To do this, they take different approaches for organizing the spectral bins used in the model, generally combining broadband components with a reduced list of specific prominent lines. To compare the models and data in a consistent way, it was chosen to integrate the flux in each of the NIS wavelength bands into a single number. The NIS-1 band is dominated by coronal lines, while transition region lines dominate the NIS-2 bandpass.

Figure 3 compares the CDS measurements against the various models. In the coronally dominated NIS-1 channel, the Hinteregger and EUV97 models follow each other quite closely, with the EUV97 values being consistently ∼37% higher than the Hinteregger values. Each starts out lower than the CDS values, and then gradually increases to match CDS, and even exceed it in the case of EUV97. The SOLAR2000 model starts out above the CDS measurements, and then gradually merges with the Hinteregger model as the solar activity rises. The EUVAC model predictions are consistently lower than the CDS measurements, by about a factor of 2. On the other hand, the overall shape of the EUVAC solar cycle variation is most consistent with that of CDS, as shown by the flat EUVAC to CDS ratio.

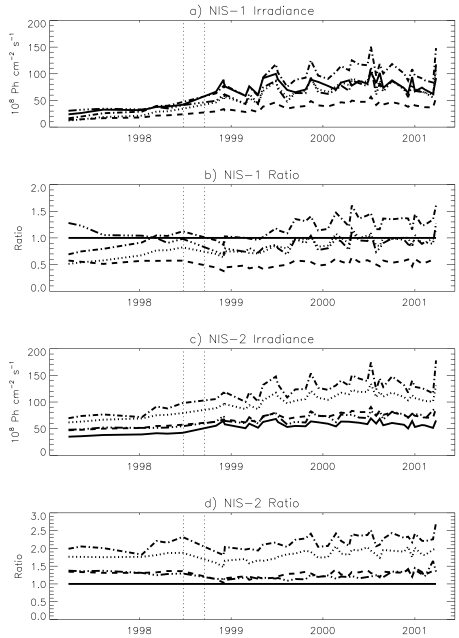

Figure 3. Comparison of the total integrated irradiance in each wavelength band measured with CDS (solid) against the Hinteregger (dot), EUVAC (dash), EUV97 (dot-dash), and SOLAR2000 (dot-dot-dot-dash) models. In panels (a) and (c) are shown the total integrated irradiances in the two NIS wavelength bands, and in panels (b) and (d) are the ratios of the models to the measurements. NIS-1 is dominated by coronal lines, while NIS-2 is dominated by transition-region lines. The two vertical dotted lines in each plot represent the period when SOHO was not pointed at the Sun.

The situation is quite different for the transition region dominated NIS-2 channel. There, the EUV97 and Hinteregger models are consistently above the CDS measurements, by factors of 2 and 1.6 respectively, while the EUVAC and SOLAR2000 models are only slightly above the CDS measurements. The overall variation over the solar cycle of each model is also consistent with the CDS measurements.

Figure 4 shows scatter plots of each of the models against the CDS NIS-1 measurements. The low values on the lower right are all from before SOHO's accident, while the values on the left are all from

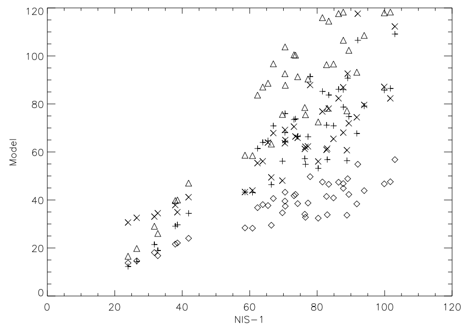

Figure 4. Scatter plots of the CDS irradiances against the Hinteregger (+), EUVAC (◇), EUV97 (△), and SOLAR2000 (×) models. All data are in units of 10^8 *Ph cm*$^{-2}$ *s*$^{-1}$*.*

after the recovery. It's evident from Figure 4 that the average behavior of each model after recovery can be characterized as an extenuation of the pre-accident behavior. It's also evident that the SOLAR2000 model is the only one that cannot be extrapolated back to the origin. There appears to be a significant solar minimum flux in SOLAR2000 which is not present in the other models, and which is not supported by the CDS measurements. All the models have high correlation coefficients of 0.85–0.89 when compared with the CDS measurements, in both NIS channels. If the correction factor of 1.447 had not been applied to the post-recovery NIS-1 data, then the correlation coefficients would have been slightly smaller for all but SOLAR2000.

3. VARIATION OF INDIVIDUAL LINES

As was previously stated, the various EUV irradiance models being considered here are designed primarily to model the integrated flux. However, there are several spectral lines which can be extracted from all of the models and compared against the CDS measurements. The ratios of the model predictions for these lines to the measured irradiance from CDS are shown in Figures 5 and 6.

The only individual line in the NIS-1 bandpass which can be extracted from all of the models is the Mg IX line at 368 Å. The behavior of the model to CDS ratios for this line is very similar to that of the full NIS-1 bandpass.

On the other hand, there is considerable variation between the four spectral lines which can be intercompared within the NIS-2 bandpass. For example, the SOLAR2000 model predictions for the O IV multiplet at 554 Å are consistently higher than the CDS measurements, while the predicted He I 584 Å irradiances are consistently somewhat lower. Other models show similar differences from line to line.

An interesting line in the NIS-2 band is the blend of the Mg X and O IV emission at 610 Å. This is the

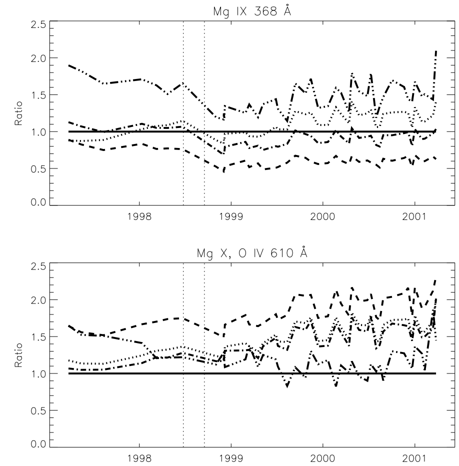

Figure 5. The irradiance variation of specific coronal spectral lines from the models divided by the corresponding CDS measurements. The line types are as in Figure 3.

only one of the lines in within the NIS-2 bandpass which can be characterized as at least partially coronal. The ratio of the SOLAR2000 model to the CDS measurements for this line starts high in early 1997, and then slowly falls through 1997 and 1998, until it finally levels out after the SOHO recovery in late 1998. This behavior matches very closely that seen in the coronally-dominated NIS-1 bandpass. The other models produce ratios for this line which also act more like that seen for NIS-1 than for NIS-2. This strongly suggests that the differences between the models and CDS is solar in nature, rather than simply being due to the CDS calibration.

4. HE II AND SI XI 304 Å

Two other lines whose irradiances can be extracted from the CDS data are the He II and Si XI lines at 304 Å. These lines are seen in second order within the NIS-2 channel. When the CDS NIS-2 measurements were compared against the model predictions in Figure 3, these two second order lines were filtered out, so as to not affect the comparison.

Figure 7 shows the combined irradiance of these two lines compared against the model predictions. Although CDS can separate the He II and Si XI emissions, the combined signal is displayed for ease of comparison with the models. Two features are evident from the data. First, in all the models except SOLAR2000, there is a downward step in the ratios of about 20–30% between the pre- and post-accident periods. A similar step is seen in the CDS to SEM comparison in Figure 2, which may indicate that this feature is due to the second order 304 Å component to the reconstruction of the SEM bandpass. Although there is no such step evident in the comparison to SOLAR2000, that model predicts an irradiance which starts out 50% higher than the CDS mea-

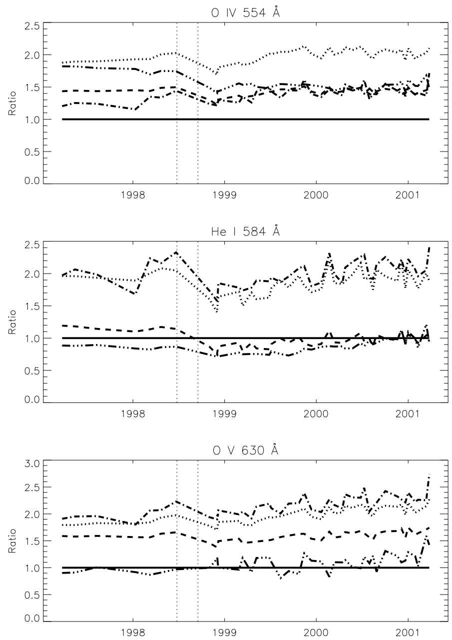

Figure 6. The irradiance variation of specific transition region spectral lines from the models divided by the corresponding CDS measurements. The line types are as in Figure 3.

surements, and which rises significantly faster. The other models also predict a slightly more rapid rise than CDS, but only by about half the SOLAR2000 prediction.

As discussed earlier, a correction factor of 1.167 was applied to the post-recovery data at 304 Å (second-order). If this correction factor was not applied, then all the models except SOLAR2000 would be compatible with the CDS measurements within 20%. However, the discrepancy between the SOLAR2000 model predictions and the CDS measurements would become worse.

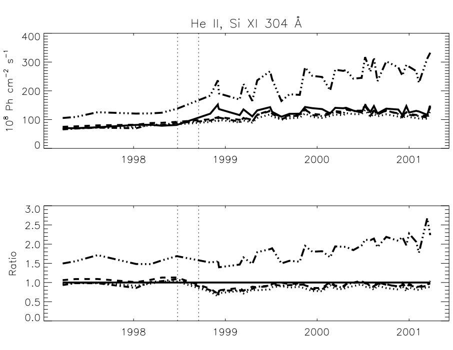

Figure 7. The irradiance variation of the combination of the He II and Si XI lines at 304 Å. The upper panel shows the total irradiance in these two lines. The lower panel shows the ratios of the models to the CDS measurements. The line types are as in Figure 3.

5. CONCLUSIONS

We have demonstrated that CDS is capable of measuring the solar EUV irradiance spectrum over a significant fraction of solar cycle 23. Comparison of the integrated NIS spectral bandpasses to several irradiance models shows significant differences between the models, and with the CDS measurements. In the coronally dominated NIS-1 bandpass, the EUVAC model most closely replicates the shape of the solar cycle variation as seen by CDS, but is a factor of 2 lower in absolute numbers. The SOLAR2000 model predicts coronal solar minimum intensities which are substantially larger than the other models or the CDS measurements. In the transition-region dominated NIS-2 channel, all the models are consistent with the measured shape of the solar cycle variation, and the EUVAC and SOLAR2000 models are also consistent with the measured values. None of the models replicated the CDS measurements in both of the bandpasses. However, the SOLAR2000 comes closest in absolute terms to the CDS measurements, while EUVAC comes closest in replicating the shape of the solar cycle variation.

The comparison between the models and CDS measurements are statistically consistent with the assumed 1.447 post-recovery correction for NIS-1. However, there appears to be an inconsistency between the 1.167 post-recovery correction factor assumed for 304 Å and the models, except perhaps for SOLAR2000. The agreement would be improved if no correction were applied. The SOLAR2000 model predicts higher values and a much stronger solar cycle variation at 304 Å than any of the other models, or the CDS observations.

ACKNOWLEDGMENTS

This work was supported by NASA grant S-34873-G.

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